INNOVATIVE UFC STRUCTURES IN JAPAN

Hiroyuki Musha (1), Hikari Ohkuma (2) and Takeshi Kitamura (2)

(1) Technology Center, TAISEI Corporation, Yokohama, JAPAN

(2) Civil Eng. Tech. Promotion Div., TAISEI Corporation, Tokyo, JAPAN

Abstract

The technologies used in Japan for designing and constructing bridges and slabs with UFC (Ultra-high strength Fiber-reinforced Concrete) have advanced over the past ten years. This paper describes two recent UFC applications: the Kayogawa Bridge, and the Runway D extension at Tokyo International Airport.

The Kayogawa Bridge was the first railway bridge in the world to be constructed of UFC. The use of UFC resulted in a thinner slab and a lower project cost. This paper describes the design and construction of this bridge, as well as the results of displacement and noise measurements.

The Runway D extension project is still the world's largest application of UFC. Approximately 6,900 UFC slabs with a total volume of 22,000 m^3 were placed in a 192,000 m^2 area of Runway D. Using UFC rather than conventional concrete reduced the weight of the slabs by 56%. This paper describes the design and mass production of these slabs.

Résumé

D'importants progrès ont été réalisés au Japon ces dix dernières années dans la conception et la technique de construction de nombreux types de ponts et de plates-formes en BFUP (bétons fibrés à ultra-hautes performances). On présente dans cet article deux projets récents. Le premier est le pont Kayogawa, premier ouvrage ferroviaire en BFUP au monde. L'usage du BFUP a permis d'atteindre une faible épaisseur de tablier et de réduire le coût total du projet. L'article relate les grandes lignes de la conception et de la construction du pont, ainsi que les résultats des mesures de flèche et de bruit des vibrations de l'ouvrage. Le second concerne la production massive de dalles en BFUP pour la piste D de l'aéroport international de Tokyo (Haneda), qui constitue l'application la plus importante de BFUP en volume pour un seul projet. Environ 6900 dalles de BFUP (soit environ 22 000 m^3) ont été mises en place pour constituer les 192 000 m² de la piste D. Le BFUP a rendu possible une réduction de 56% du poids propre par rapport à une solution en béton traditionnel. On présente les grandes lignes de la conception de cet ouvrage et de la production des dalles.

1. INTRODUCTION

The technologies used in Japan for designing and constructing footbridges, highway bridges, railway bridges, and airport runway slabs with UFC (Ultra-high strength fiber-reinforced concrete, or Ductal®) have advanced in the past ten years. The first UFC structure in Japan, the Sakata Mirai footbridge, was completed in October 2002. Since then, more than twenty UFC bridges have been constructed. UFC also has been used extensively for airport runway slabs. These structures incorporate various technologies that were developed to characteristics of UFC.

This paper describes two recent UFC applications: the Kayogawa Bridge and the Runway D extension at Tokyo International Airport (Haneda Airport).

The Kayogawa Bridge was the first railway bridge in the world to be constructed of UFC. Due to river improvements, the old Kayogawa Bridge was to be replaced with a pre-stressed concrete U-girder. The girder originally was designed to have a 390 mm-thick slab, which would require raising the railroad track to satisfy a new specification for the estimated high-water level (HWL). By using UFC, however, a slab just 250 mm thick could be constructed, thereby avoiding the need to raise the railroad track and reducing the cost of the project. This paper describes the design and construction of this bridge, as well as the results of displacement and noise measurements.

The second project was the extension of Runway D at Tokyo International Airport (Haneda Airport). Approximately 6,900 UFC slabs totalling 22,000 m^3 in volume were placed in a 192,000 m^2 area of Runway D, making the project the world's largest application of UFC. Each slab was 7.82 m x 3.53 m in size and pre-tensioned in two directions. By using UFC rather than conventional concrete, the weight of the slabs was reduced by 56 %. This paper describes the design and mass production of the slabs.

2. KAYOGAWA UFC RAILWAY BRIDGE

The Kayogawa Bridge (Figure 1) in Japan was the first railway bridge in the world to be constructed using UFC.

Due to river improvements, the old railway bridge, a steel deck bridge 9.6 m in length with a girder height of 695 mm, needed to be replaced with a low-maintenance concrete bridge. As a result of river improvements and changes in the flood control plan, this new bridge had to be 1.65 times longer than the original bridge and have a higher girder to accommodate a higher estimated high-water level (HWL). To satisfy these conditions without changing the height of the railroad track (Figure 2), the concrete lower slab had to be 250 mm thick. A slab constructed of conventional concrete, however, would have to be 390 mm thick, which would require changing the height of both the railroad track and an adjacent station, thereby increasing the cost of construction.

By using UFC, a slab just 250 mm thick could be constructed, avoiding the need to change the height of the railroad track and reducing the total cost of the project. The designs of a UFC bridge and a conventional concrete bridge are compared in Table 1.

This paper describes the design and construction of this bridge, as well as the results of displacement and noise measurements. The overview of design and construction of this bridge are reported here, together with the results of displacement measurement and noise measurement of this bridge.

Figure 1: Kayogawa UFC railway bridge

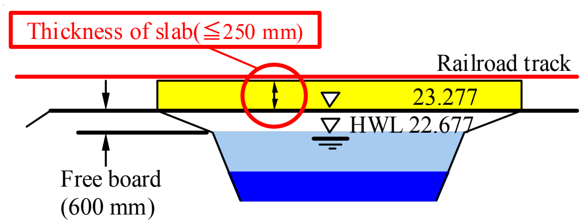
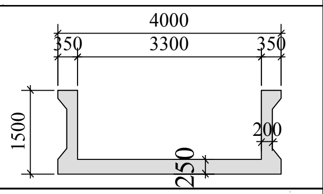
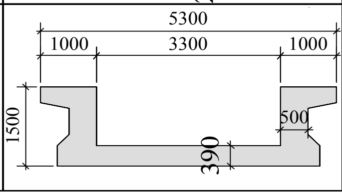


Figure 2: Design conditions for slab

Table 1: Comparison of slabs for UFC and conventional concrete bridges

	Cross section	Area of cross section	Design load	Flexural rigidity
UFC through bridge		A=1.6 m^2 (0.5)	Girder: 700 kN (0.54) Track: 500 kN Ballast: 500 kN Train: 1100 kN Total: 2300 kN (0.79)	EI=1.6×10^7 kN・m^2(0.76)
Conventional concrete through bridge		A=3.2 m^2 (1.0)	Girder: 1300 kN (1.00) Track: 500 kN Ballast: 500 kN Train: 1100 kN Total: 2900 kN (1.00)	EI=2.1×10^7 kN・m^2(1.00)

2.1 Design

The design of this bridge is based on the Design Standards for Railway Structures, with occasional references to Commentary [1], and UFC Guidelines [2]. As no precedent existed for using UFC in railway bridges, the thinner slabs were difficult to evaluate. Therefore, the characteristics of UFC were subjected to numerous FEM analyses and other examinations.

The thin UFC member also results in a bridge with less flexural rigidity than a conventional prestressed concrete bridge. The vibration and deflection characteristics of this UFC bridge were analyzed and compared with those of a conventional bridge.

2.1.1 Thickness of member

Table 1 compares the Kayogawa Bridge with a conventional concrete bridge. The top flange width of 350 mm was determined by the minimum size of the tendon anchorage for the longitudinal prestressing strands in the main girder. The lower slab thickness of 250 mm was determined by the arrangement of the longitudinal and lateral sheaths for the prestressing strands. Three-dimensional FEM analysis confirmed that the principal stress was within the limits for UFC tensile stress (-8N/mm^2). (Figures 3 and 4)

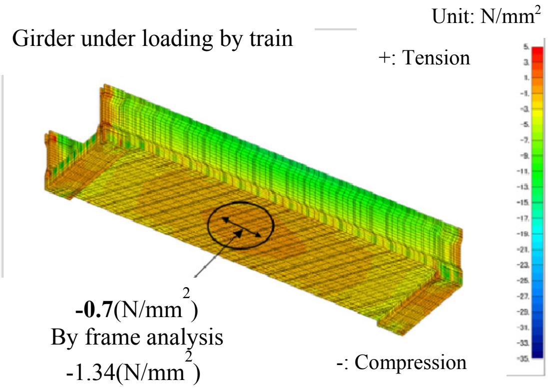


Figure 3: Longitudinal stress

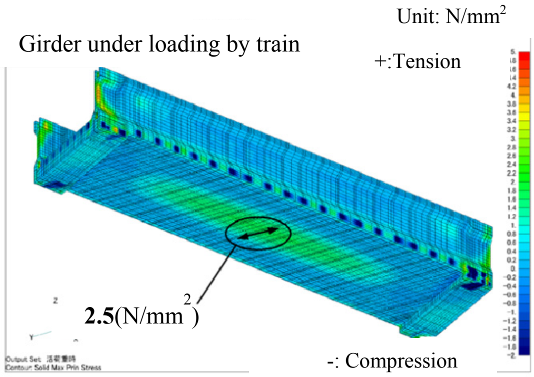


Figure 4: Principal stress

2.1.2 Resistance to lateral buckling

The top flange of the girder is 350 mm wide, which is less than the minimum width of 435 mm prescribed by the railroad standard. Therefore, the girder's resistance to lateral buckling was evaluated using Euler buckling analysis with three-dimensional FEM analysis. (Figure 5). In this analysis, the web reached the lateral buckling limit when the acting load was approximately 155 times greater than the ordinary fluctuating load, confirming that the bridge can resist lateral buckling.

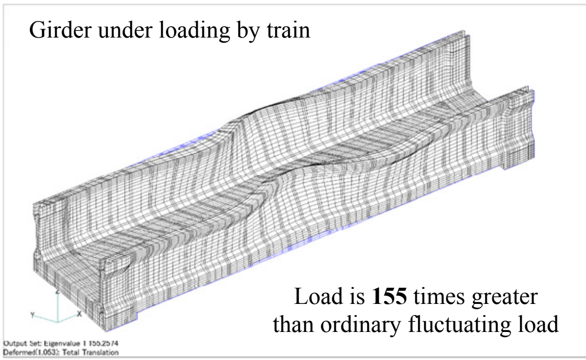


Figure 5: Buckling mode analysis

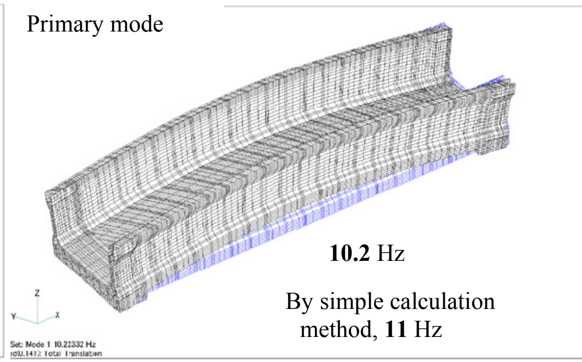


Figure 6: Primary mode of characteristic frequency

2.1.3 Vibration properties

Since the members of this UFC bridge are thin, the natural period tends to be longer than that of a conventional concrete bridge. Therefore, the bridge's vibration properties were evaluated to determine the bridge's resonance when a train passed over it. The characteristic frequency was calculated using a simple calculation method, $f = \pi/(2 \times Lb2) \cdot \sqrt{((EI \cdot g)/D)}$, and three-dimensional FEM analysis.

Using the simple calculation method, the characteristic frequency of the UFC bridge was 11.1 Hz, while that of a conventional concrete bridge was 11.0 Hz. Using eigenvalue analysis and FEM analysis (Figure 6), the primary mode frequency was 10.2 Hz for both the concrete bridge and the UFC bridge.

2.1.4 Deflection

The design deflection limit [δ] value was set to [δ < span/500] assuming the stability of a running train during normal service. The deflection was calculated using two-dimensional frame analysis and three-dimensional FEM analysis with consideration of the skew angle. Two-dimensional frame analysis returned a deflection value of 4.8 mm, while FEM analysis returned a deflection value of 5.0 mm. (Figure 7). In both cases, the values were well below the deflection limit value of 29.0 mm.

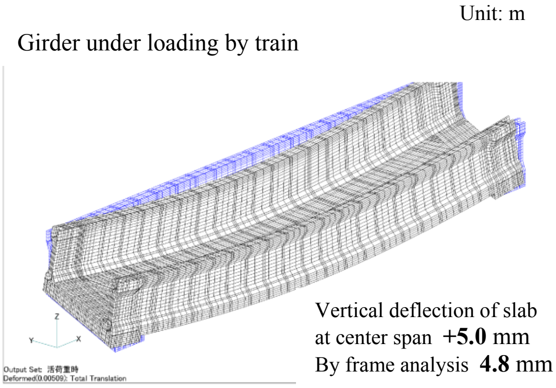


Figure 7: Deflection

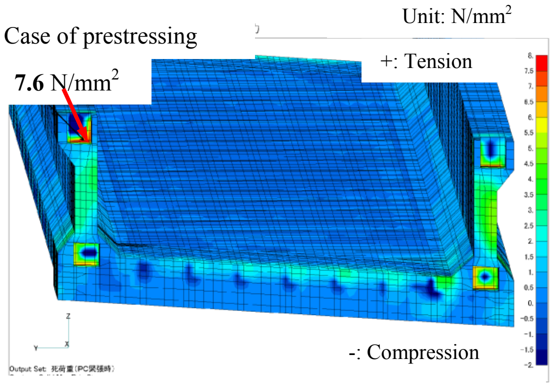


Figure 8: Principal stress of back side of tendon anchorage

2.1.5 Reinforcement rebar

Conventional design requires rebar reinforcements in the tendon anchorage and the unseating prevention stopper. Because UFC structures generally do not require reinforcement rebar, the need for rebar in this bridge was examined. Three-dimensional FEM analysis of the splitting tensile stress at the back of the tendon anchorage (Figure 8) showed that the principal stress was 7.6 N/mm^2, which is below the limit level of 8.0 N/mm^2 for UFC tensile stress.

2.2 Construction

The bridge was constructed in a factory using the pre-cast segment method. The segments were then transported to the construction site. A 65-ton crane placed the segments in a segment assembly yard (Figure 9). Cast-in-place UFC was then poured into the spaces between the segments.

Figure 9: Transporting the segments

Figure 10: Before lateral transfer

Four 12S12.7 mm steel strands for prestressed concrete were placed in the web. Seven 1S21.8 mm steel strands were placed in the lower slab. After confirming the strength of the filled spaces, the steel strands were prestressed, unifying the segments into a single girder. The old bridge was replaced with the new bridge in the early morning hours to avoid disrupting normal rail services. The process took only three hours. (Figure 10)

2.3 Measurement

As this was the first railway bridge to be constructed using UFC, the deflection and characteristic frequency were measured after services resumed in order to evaluate the design and construction. Noise levels as trains passed over the bridge also were measured to evaluate the bridge's noise properties.

2.3.1 Characteristic frequency

Design analysis showed that this bridge has the same characteristic frequency as a conventional concrete bridge. This was verified by measuring the bridge's natural frequency. The primary mode frequency of the drive point impedance at the centre of the lower slab was 12 Hz (Figure 11), which is equivalent to the value obtained using the simple calculation method in the design stage.

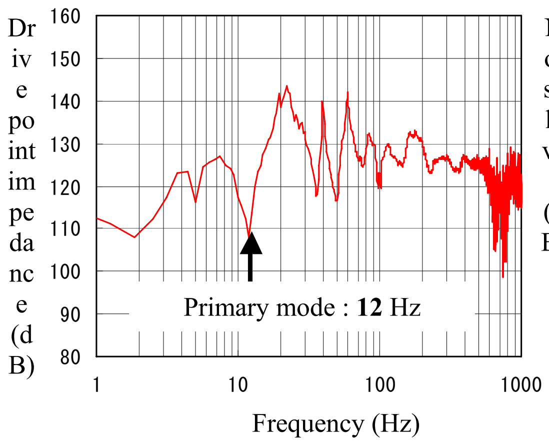


Figure 11: Drive point impedance

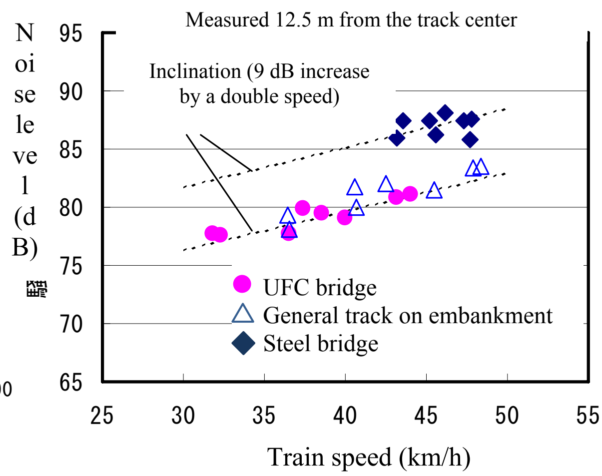


Figure 12: Noise levels

2.3.2 Noise level

Noise levels were measured while trains passed over the UFC bridge. The results were compared with the noise levels measured on a track on an embankment and on a through-type steel bridge with an open floor structure. Figure 12 shows the relationships between the noise level and the train speed. The noise levels for the UFC bridge and the track on an embankment were the same. Moreover, the tendency along the degree of leaning of 30log10V (9 dB increase by a double speed) in speed V was almost seen in the noise level as it was reported in a previous study. The noise levels for the UFC bridge were lower than those for the steel bridge by more than 5 dB at each speed.

3. MASS PRODUCTION OF UFC SLABS

Approximately 6,900 precast UFC slabs were placed in a 192,000 m^2 area of Runway D at Tokyo International Airport (Haneda Airport). Because the UFC slabs must withstand aircraft loads, a UFC slab structure with pre-tensioning in two directions was developed. A dedicated mass-production system produced 6,900 UFC slabs in two years.

Such a large UFC slab with this type of structure is unprecedented. Moreover, the volume of UFC used—22,000 m^3—made this project the world's largest application of UFC. Since a summary of the design and an evaluation of the loading already have been reported [3], this section will describe only the UFC slab structure and the mass production system.

3.1 Structure of UFC precast slab

Figure 13 shows the structure of a UFC precast slab. The slab is 7.82 m long, 3.53 m wide and just 75 mm thick, and has a simple support structure with two long sides. Pre-tensioning in two directions was chosen over post-tensioning to reduce the cost of mass production. Twenty ribs, each 250 mm long, are arranged perpendicular to the transverse direction. One rib contains three longitudinal prestressing strands, each 19.3 mm in diameter. Each slab, therefore, contains sixty such strands. The design prestressing force in the longitudinal direction is extremely large—17,418 kN—to support aircraft loads. Twenty-four strands, each 15.2 mm in diameter, are arranged horizontal to the transverse direction, and the design prestressing force is 4,637 kN. The average (conversion) thickness of a slab is about 135 mm. If conventional concrete (design strength: 50 N/mm^2) had been used, the average slab thickness would have been about 320 mm. Using UFC slabs rather than conventional concrete slabs reduced the dead load (ratio of average dead loads) by about 56%.

Even though this slab does not contain rebar, the many prestressing strands in two directions and the significantly large prestressing force ensure excellent load performance.

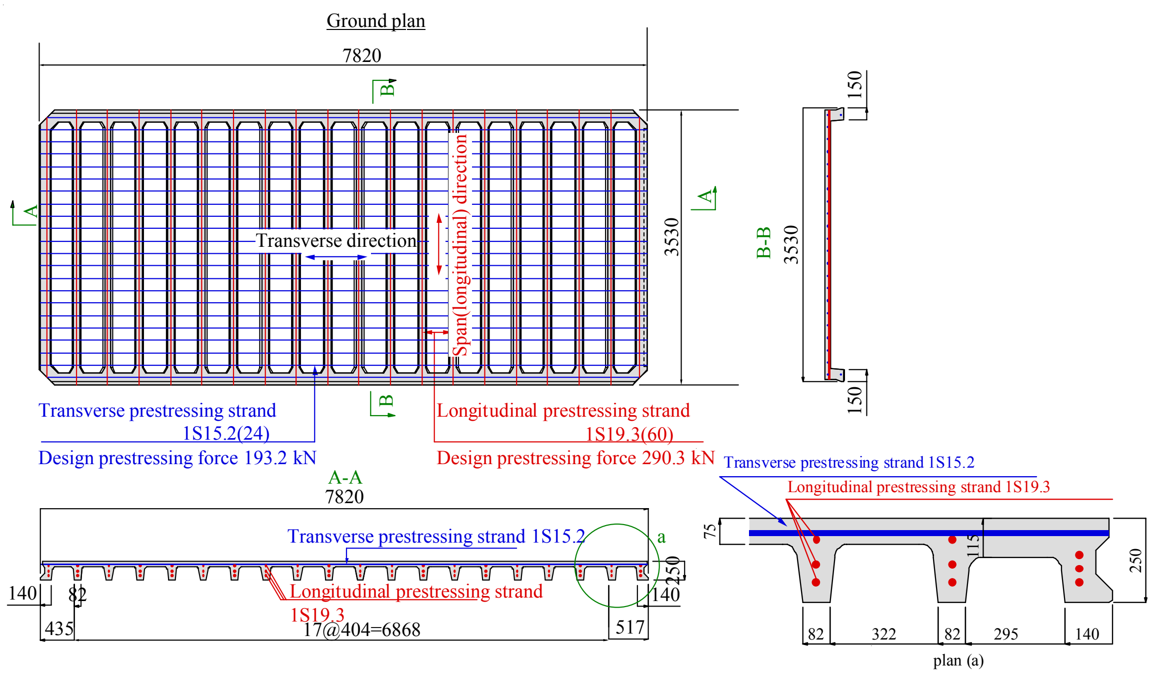


Figure 13: Structure of UFC slab

3.2 Mass production system

Figure 14 shows the layout of the UFC slab factory. Huge equipments applied two-direction pre-tensioning. This was the world's largest factory for UFC products.

A dedicated UFC batching plant (Figure 15) on the factory site was capable of mixing 15 m^3 of UFC per hour and producing 70 m^3 of UFC (twenty slabs) in five hours.

The roofed area of the factory was 45 m wide and 200 m long. Each of the two production lines, A and B, had a production yard, steam curing tank, prestressing steel-end processing area, and inspection area. (Figure 14).

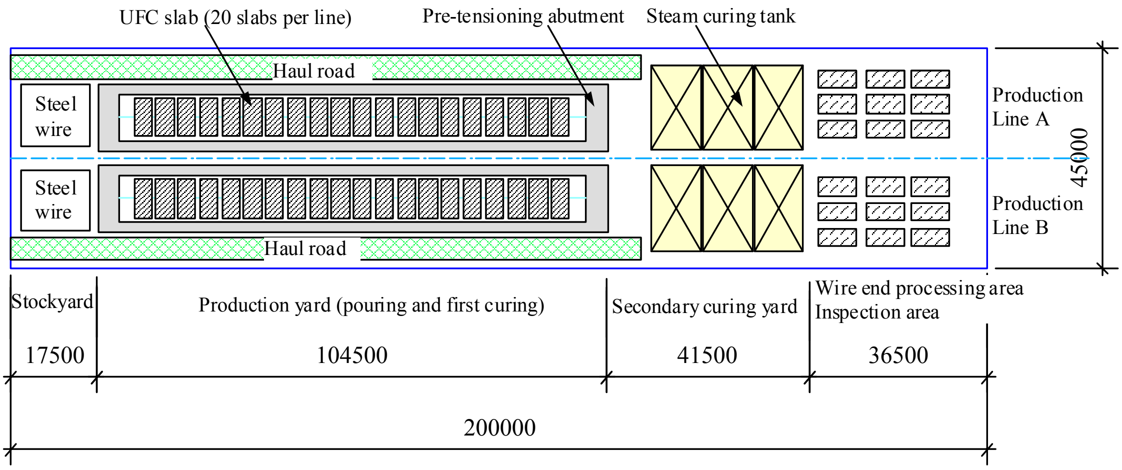


Figure 14: Layout of UFC slab factory

Figure 15: UFC batching plant

Figure 16: UFC slab production line

Figure 17: Pouring UFC into a slab form

The production yard for each line contained concrete abutments for pre-tensioning, with twenty forms within the abutments (Figure 16). Each line had a three-day production cycle and produced 60 slabs a week; together, the two lines produced 120 slabs a week. The UFC was mixed in the batching plant and then transported to the production yards, where it was poured into forms containing pre-tensioning cables running in two directions (Figure 17). On the following morning, after confirming that the strength exceeded 45 N/mm^2, prestressing was applied. The prestressing strands were then cut and the slabs transported to a steam curing tank using an overhead travelling crane.

Each line had three steam curing tanks. The slabs were steam cured at 90°C for 48 hours to ensure ultra-high strength and durability. This accelerated curing under high temperature and moisture resulted in a final strength of about 200 N/mm^2.

3.3 Mechanical properties during mass production

Table 2 lists the three types of mechanical strength obtained during mass production and their static values for comparison with the values from the UFC Guidelines [2]. The dispersion can be considered small if the coefficient of variation of the compressive strength is 5.2 % and the value is within a half degree of the value for conventional concrete.

Figure 18 shows the frequency distribution for compressive strength. Despite the data being from only one factory, the graph shows a typical normal distribution shape because an adequate number of specimens (n = 623) was available over a period of two years.

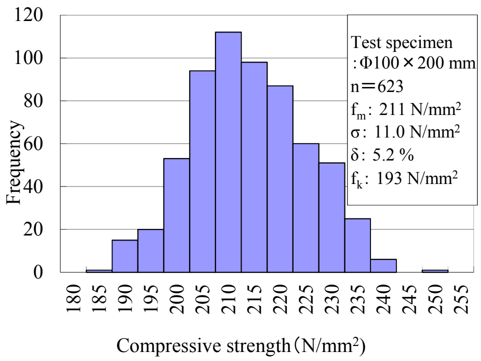


Figure 18: Frequency distribution for compressive strength

Table 2: Strength of mass-produced UFC

Statistic		Symbol	Unit	Compressive strength	First cracking	Tensile strength
Mass production	Number of samples	N	----	623	623	623
	Average	f_m	N/mm^2	211	10.2	14.6
	Standard deviation	σ	N/mm^2	11.0	0.8	2.2
	Coefficient of variation	δ	%	5.2	7.6	15.2
	Standard value	f_k	N/mm^2	193	8.9	10.9
UFC Guidelines	Satndard value	f_k	N/mm^2	180	8.0	8.8

4 CONCLUSION

4.1 UFC railway bridge

Kayogawa bridge was the first railway bridge to be constructed using UFC. Additional testing and measurements confirmed that the bridge was safe and properly designed.

Because no precedent existed for a railway bridge constructed using UFC, the girder height of a conventional concrete bridge (first draft design) was adopted in order to avoid an extreme decrease in flexural rigidity. This resulted in a safety factor of 0.5-0.7<1.0. Moreover, no problems were revealed by FEM analysis. Therefore, this bridge could be considered overdesigned in some aspects. Furthermore, since the bridge has a short span, the thickness of the member was determined by the placement of certain elements, such as the tendon anchorages, rather than by the stress. Therefore, long-span bridges that utilize the characteristics of UFC are possible.

4.2 Mass-production of UFC slabs

UFC slabs were selected for Runway D at Tokyo International Airport (Haneda Airport) because UFC offers excellent performance. Because UFC had never been mass-produced, various studies were carried out.

The results of the studies were used to build a dedicated UFC batching plant and production factory. This factory produced about 6,900 large UFC slabs. No technical problems were encountered, and the project was deemed very efficient and effective. In the background of this success, there was the accumulation of UFC technology which was developed for many years, and the step-up of more technique had been obtained by this mass production.

REFERENCES

[1] Railway Technical Research Institute (RTRI), Design Standards for Railway Structures and Commentary (Concrete Structures), 2008
[2] JSCE (Japan Society of Civil Engineers), "Guidelines for the Design and Construction of Ultra High Strength Fiber Reinforced Concrete (Draft)," 2004
[3] Designing and Building with UHPFRC, The Innovation and Application of UHPFRC Bridges in Japan, 2011